Modular Advanced Composite Hull-form (MACH) Technology

Progress Report
Period January- March 2002

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Grant No. N00014-01-1-0916
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Report No. UM-MACH-PR-01-3

May 2002

TABLE OF CONTENTS

Page

1. Introduction

This progress report for the project Modular Advanced Composite Hullform (MACH) Technology covers the period from January 2002 to March 2002. In this phase of work, the University of Maine is partnered with Pacific Marine & Supply Co of Honolulu, HI (PACMAR, Applied Thermal Sciences Inc of Sanford, ME (ATS), Nigel Gee and Associates of Southampton, UK, (NGA). The NAVSEA Surface Warfare Center Bethesda, MD (NSWC-CD), and Naval Sea Systems Command Undersea Warfare Center Newport, RI (NAVSEA Newport) are also involved in the effort.

1.1 Objectives

The long-term objective of the program is to develop and demonstrate hybrid composite /metallic structure and joining concepts and technology for application to naval ship hulls. It is envisioned to develop hybrid joint concepts and technology that will have as broad of impact as possible on Navy vessels. The technology will be investigated for two types of generic hybrid construction: (a) The hybrid hull concept where the out-of-plane attachment of dissimilar composite and metallic structure (e.g., the attachment of composite panels to a supporting metallic framework) for the HYbrid Small Waterpalne Area Craft (HYSWAC) and (b), the in-plane attachment of dissimilar metallic and composite structure for the hybrid hull (e.g., the attachment or connection for a hybrid composite to metallic ship hull structure). The technology will be demonstrated at both the joint component level and at the hybrid system level. As a secondary objective, the smart skin concept for structural monitoring will be investigated as part of MACH, and the HYSWAC structural monitoring system will leverage the results.

1.2 Current Work

The primary tasks undertaken during this period include:

1. Continuing work on connections.
    a) Development of a plan for study of stress relaxation in bolted connections
    b) Development of a plan for study of adhesives in hybrid connections in conjunction with the AHFID program.
    c) Study of the Structural Response of Connections
    d) Manufacturing processes for composite panels.
    e) Methods for fabrication of co-cured hybrid connections.
2. Preliminary results of cavitation erosion protection study.
3. Continuing work on structural monitoring systems.
4. Completion of the design of the H-body for HYSWAC.

1.3 Program Review Meeting

UMaine, PACMAR, ATS, NSWC-CD and ONR staff supported a semi-annual program review held at Pacific Marine, Honolulu, Hawaii. A series of talks and presentations took place during February 11-13, 2002. Presentations that were given are documented on CD.

2. Connection Studies

2.1 Stress Relaxation in Bolted Connection

The objective of this effort is to quantify the stress relaxation of transversely compressed composites in single bolted aluminum/vinylester hybrid connection, where used where watertight seals are required. It is proposed to study similar joints at a sub-component level. From this information it can be determined which joint is best suited for the specific application. Research is proposed to study the effects of the following:

1. Effect of bolt torque and geometry,
2. Effect of stress concentrations
3. Effect of varying thickness on the constituents
4. Effects of re-applying torque to the bolts
5. Temperature/Moisture Effects

Another significant note is that at the February meeting in Hawaii a decision was made to use the DOW 8084 resin for this study in lieu of the 411 or 510e. For this reason a new set of test articles are required and are in the process of being fabricated.

2.1.1 Compression Block Pilot Test.

A compression block fixture (see Figure 2.1) was designed and fabricated. This fixture consists of relatively thick steel block, bolts and load washers for determination of bolt load. It was designed to induce a relatively uniform state of stress on the composite material.

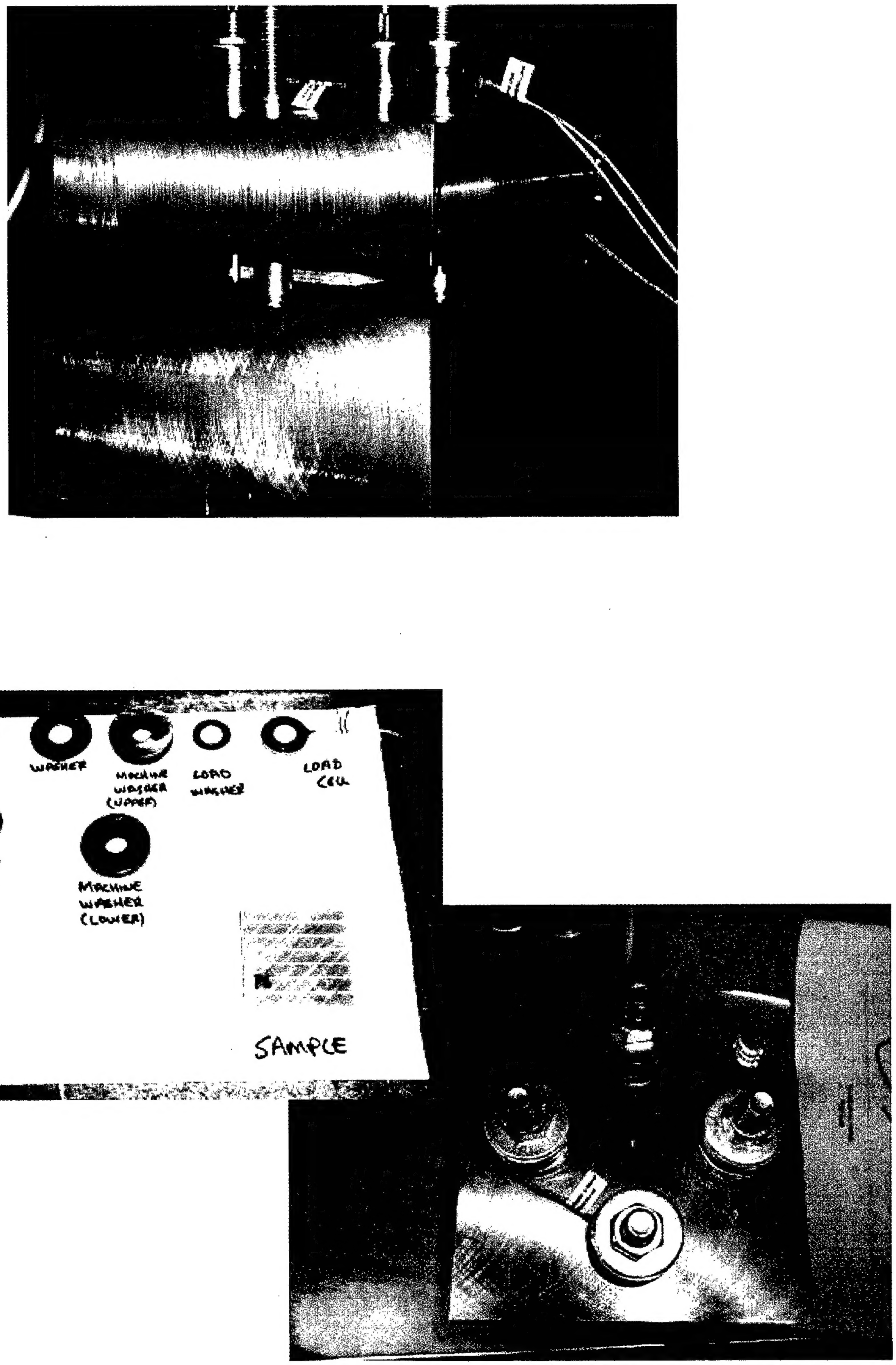


Figure 2.1 – Compression Block Apparatus

A series of pilot tests were conducted to prove out the test setup and test methodologies. Some preliminary data was taken and is included in this report. Figure 2.2 shows the results of one trial where the relaxation of the four bolts is plotted versus time. Observed in this trial is a 7-10% relaxation of bolt stress after 120 hours of loading.

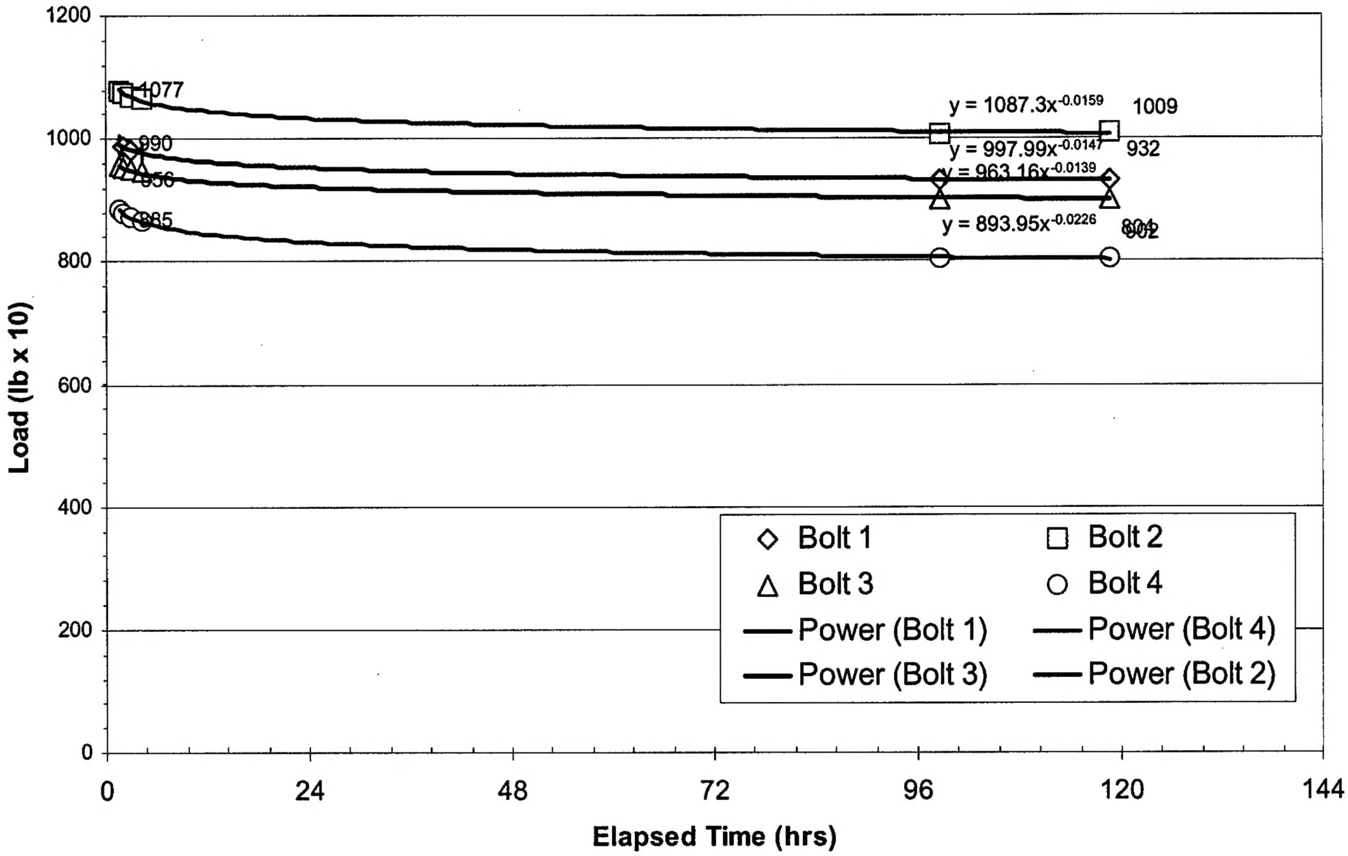


Figure 2.2 – Sample Results From Compression Block Test

2.1.2 Single Bolt Sub-component Tests.

Pilot testing of single bolts was also conducted. Figure 2.3 shows several tests of ½" and ¾" bolts running simultaneously. The test article was sized such that the thickness is nominally equal to the bolt diameter and the width of the plate is greater than 5 bolt diameters in any direction. Analytical models have shown that the stress diminishes after about three bolt diameters.

Results of pilot tests for cases with and without washers are presented in Figure 2.4. The upper set of curves are the results of the ¾" and the lower set are for the ½" bolts in the case with washers. The case with no washers shows a similar trend. Stress distribution under the bolts has an influence on the short-term relaxation. The case with washers shows an 18-20% relaxation after 120 hours whereas the case without washers shows a 20%-22% relaxation after the same period of time.

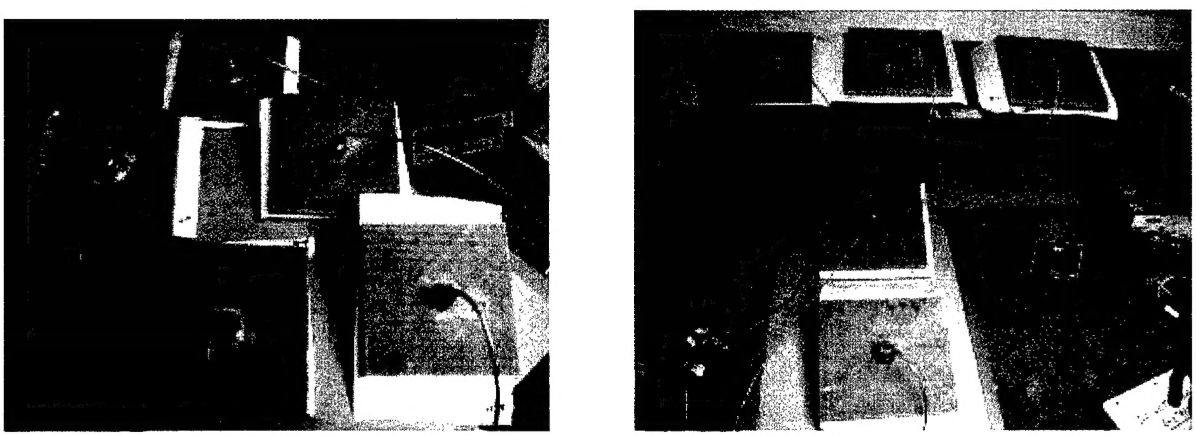


Figure 2.3 – Single Bolt Relaxation Test Apparatus

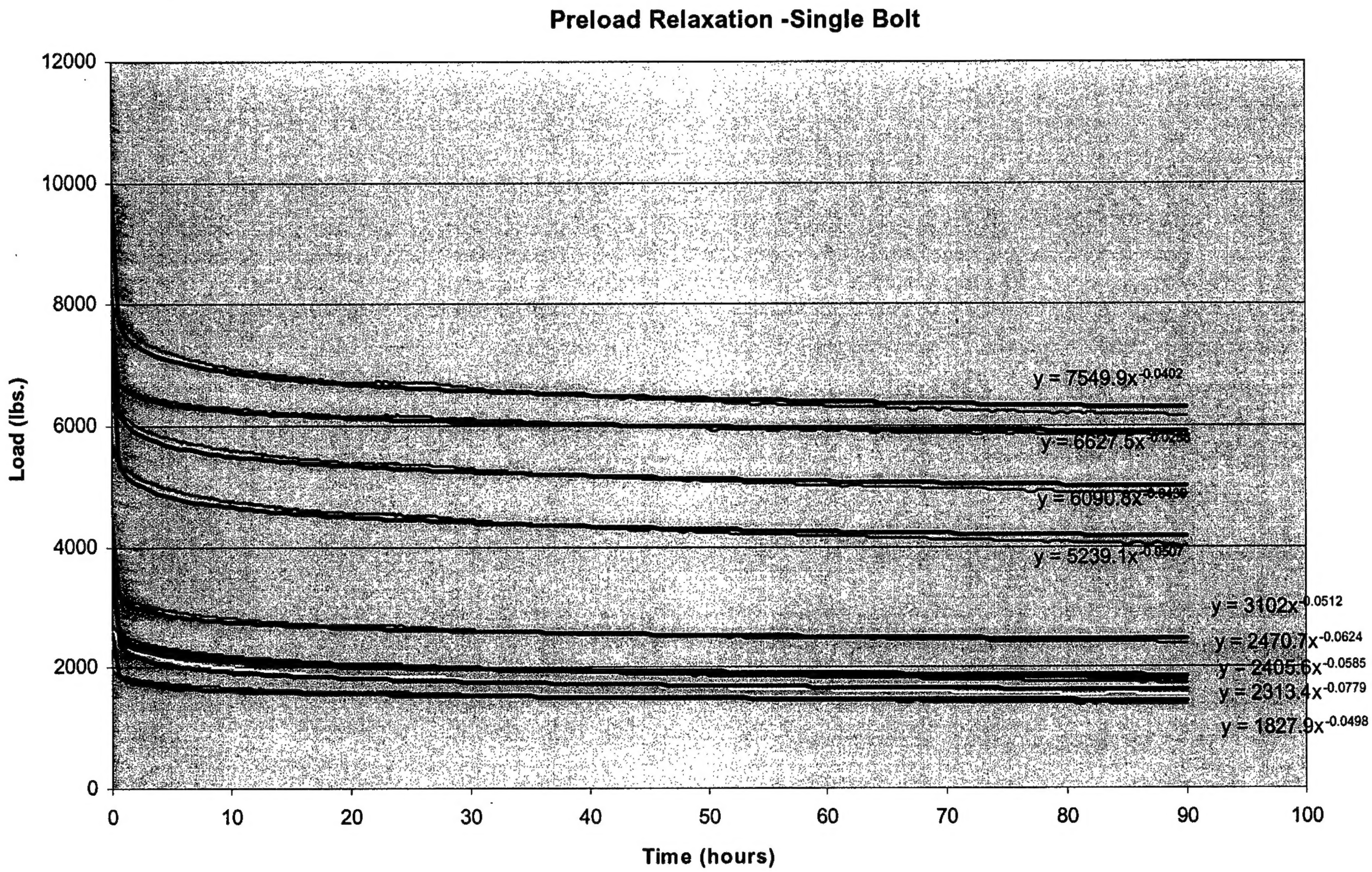


Figure 2.4 – Sample Results From Single Bolt Tests.

2.1.3 Multi-bolt Sub-component Tests.

Multi-bolt test trials were performed to verify the instrument system and usefulness of a pressure paper at the joint interface to estimate peak stresses. This study will provide data for computer models and shows the effect of adjacent bolts on the response. Figure 2.5 show a view of the preliminary set-up where 5 bolts were used in a staggered pattern. Figure 2.6 depicts the prediction of peak stresses in the connection using the pressure paper. Observed is a concentration of stress around the bolts, as expected. Also observed is an unsymmetrical loading pattern due to three bolts being placed on one side as opposed to two on the other side. A symmetric bolt arrangement is recommended for further studies. It is noted that no surface preparation of the material was used and these results are preliminary.

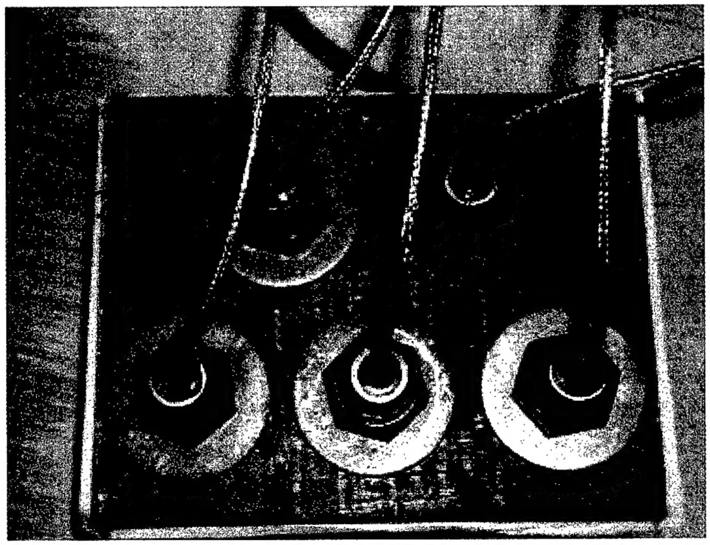


Figure 2.5 – Multi-bolt Relaxation Test Apparatus

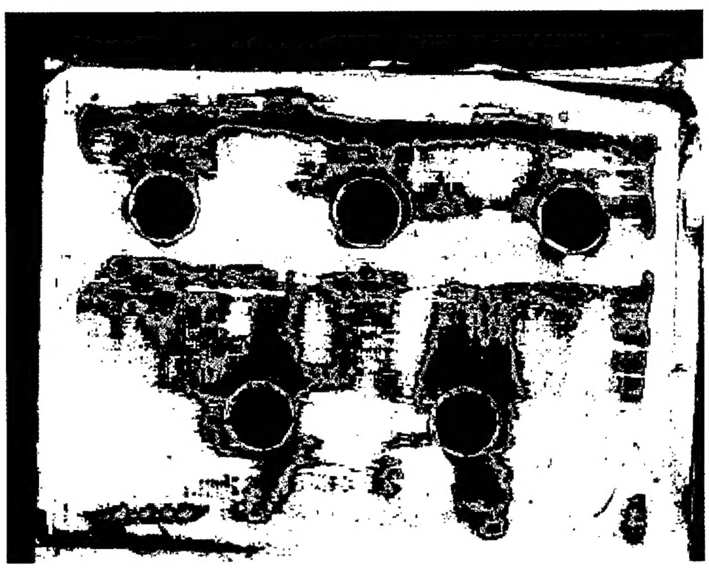


Figure 2.6 – Pressure Paper Sample Results.

2.1.4 Analysis

ATS staff has continued to develop finite element models to support the design of a bolted joint. Since the anticipated use of this connection is below the waterline the ability of the joint to maintain watertight integrity is paramount. To insure the watertight integrity of the joint using a 3 dimensional finite element model, which, incorporates contact and viscoelastic material properties to model the long-term effects of bolt relaxation on the connection was used. Figure 2.7 shows bolted connection geometry under consideration.

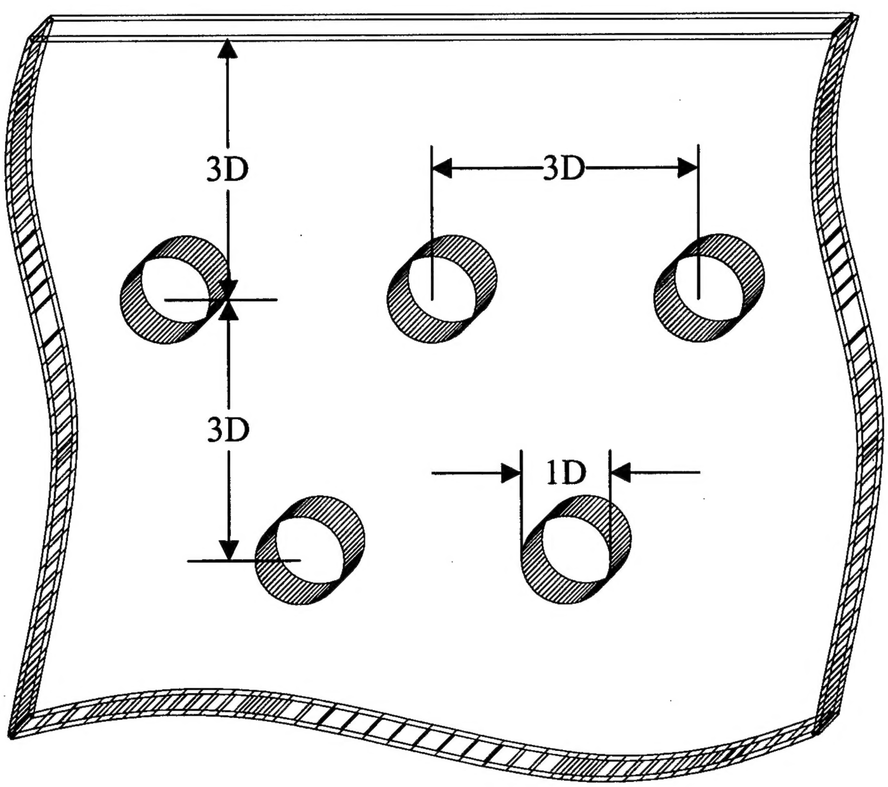


Figure 2.7 - Bolted connection under consideration

Figure 2.8 is a representative section of the FEM of the bolted joint under study. The elements shown in green are the viscoelastic composite material, while the elements that are gray represent the bolts. Contact is modeled on the surfaces under the bolt heads and along the shaft. In this model the metallic plate which the specimen is bolted to is modeled as an analytical rigid surface. Figure 2.9 shows the contact surfaces.

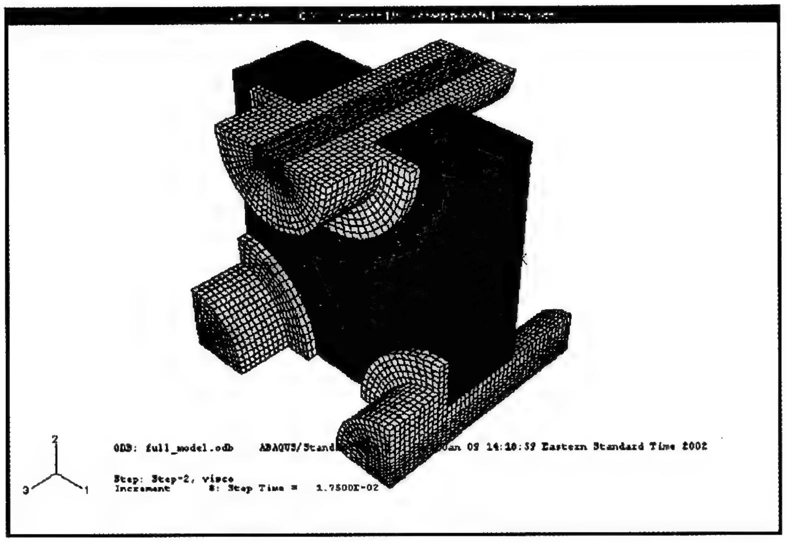


Figure 2.8 – Finite Element Model of the bolted connection

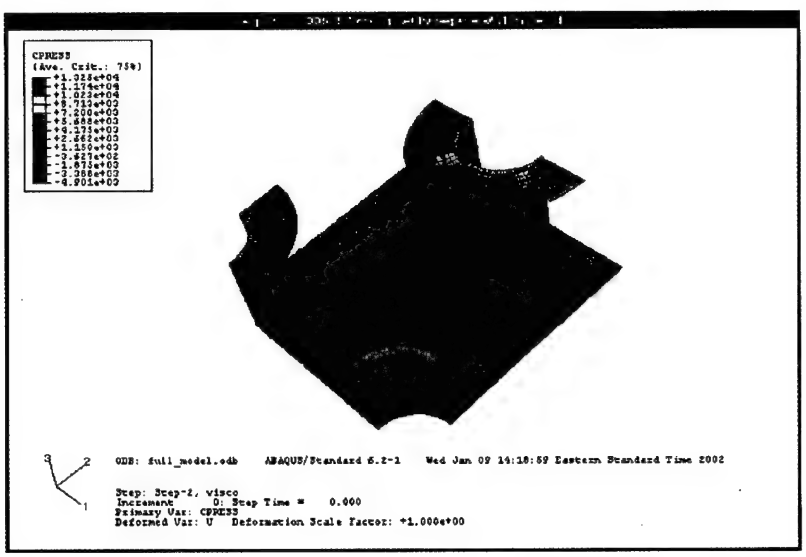


Figure 2.9 - Contact surfaces

This model has 80224 3D solid elements and 295382 degrees of freedom. The analysis contains two steps. Bolt forces are simulated by applying pressure to the bottom surface of the bolt. A nonlinear static analysis calculates the displacement around the bolt due to tensioning and the

initial contact stress between the composite material and the metallic plate. Figure 2.10 shows the contact stress developed in the region between the composite material and the backing plate.

In the model shown the dark blue region between the boltholes is 100 psi. This should generate sufficient clamping force to insure watertight integrity for the joint. The second step of the analysis would be to allow the material to relax.

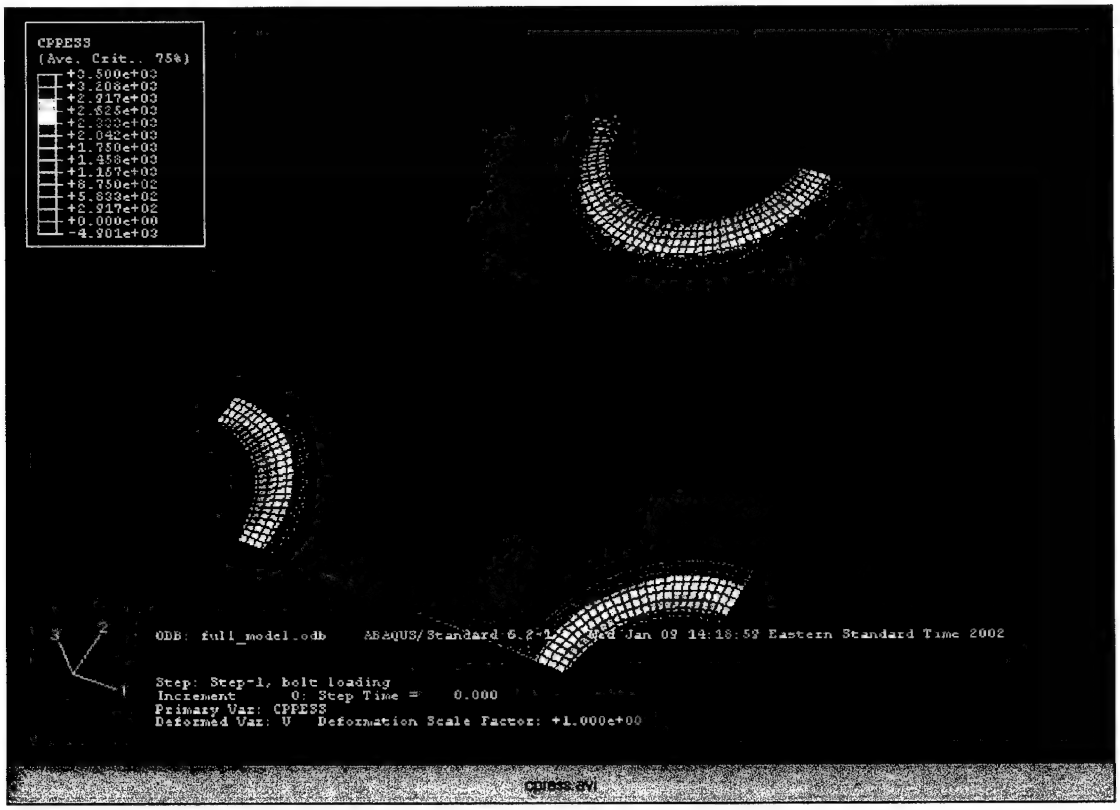


Figure 2.10 - Contact stresses

2.2 Study of Adhesives in Hybrid Connections

The University of Maine is in the process of performing and adhesive study as a combined effort between the MACH and AHFID programs. To understand the adhesive requirement needed with a large bond line thickness, compared to aerospace tolerances, it is proposed to study similar bonds at a sub-component level under loads of tension, shear, and flexure.

A study is proposed to:

1. Provide baseline data that will guide adhesive selection,
2. Quantify strength of the adhesive connections,
3. Quantify the effect of bond line thickness,
4. Quantify the effect of various connection geometry's

5. Quantify the effect of the surface preparation
6. Quantify the effect of the environment.

Geometries to be investigated are: a) single lap-connection, b) scarf joint and c) notch connection.

2.2.1 Adhesives

Adhesives for this study have been selected and the procurement process for the adhesives has been initiated. The adhesives selected are as follows:

a. Belzona 1121
b. Loctite (Hysol) 9359.3
c. Loctite 9394/2
d. Loctite (Hysol) 9430
e. SIA E2119
f. 3M 2216

2.2.2 Bondline Thickness

Bondline thickness will be controlled using shims. A set of shims was procured for this purpose. Bondline thickness of 0.1", 0.25" and 0.35 will be tested.

2.2.3 Surface Preparation

Surface preparation is to consist of mechanical abrasion, grit blasting or silane primers. Figure 2.11 show a depiction of the mechanical abrasion process.

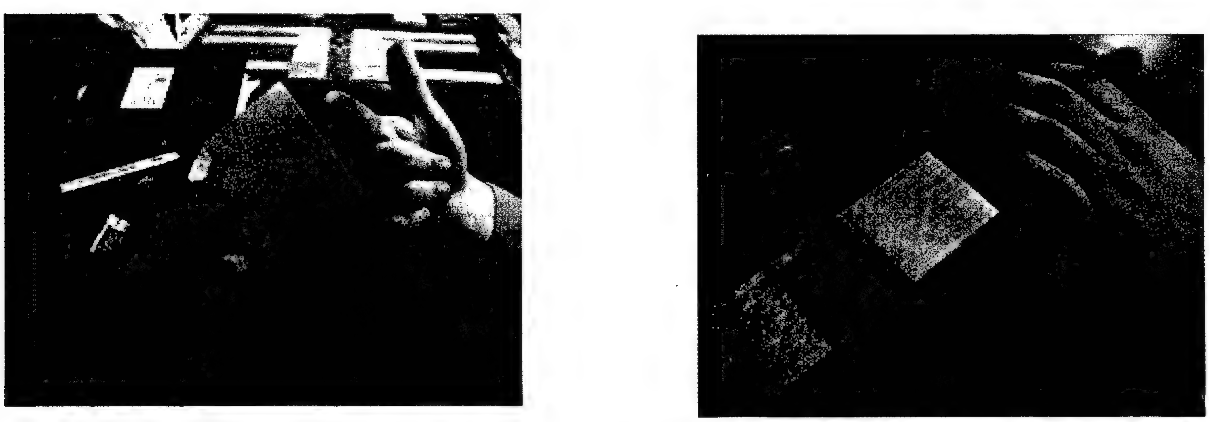
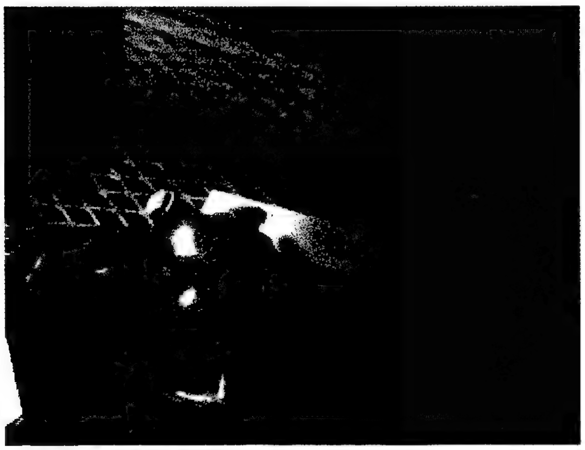


Figure 2.11 – Adhesive Joint Surface Preparation – Mechanical Abrasion

Grit blasting of the metallic surface will be done in a blast cabinet as shown in Figure 2.12.



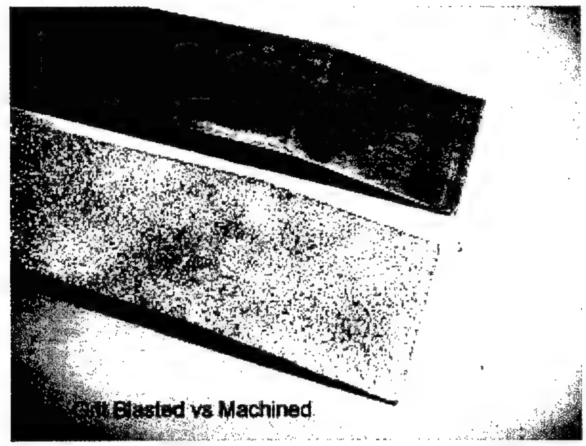


Figure 2.11 – Adhesive Joint Surface Preparation – Grit Blasting

2.2.4 Test Plan Development

Table 2.1 presents the test matrix to be used for the initial part of this study. Screening tests will be conducted using the six adhesives described in Section 2.2.1 by conducting tensile lap shear tests with a bondline of 0.1". Workability of the adhesives will also be recorded during these tests. The top adhesive candidate will then be downselected and placed through a host of other screening tests including, tension, flexure and shear on lap, notch and scarf joint test articles. Test at elevated temperature and humidity will also be performed.

Table 2.2 - Test Matrix

Joint Type			Test Condition								
			Shear -RTD			Tension -RTD			Flexure - RTD		
	Adhesive	Bond Line	Prep 1	Prep 2	Prep 3	Prep 1	Prep 2	Prep 3	Prep 1	Prep 2	Prep 3
Lap	A	T1	3	3	3	3	3	X	3	3	X
	B	T1	3	3	3	3	3	X	3	3	X
	C	T1	3	3	3	X	X	X	X	X	X
	D	T1	3	3	3	X	X	X	X	X	X
	E	T1	3	3	3	X	X	X	X	X	X

			Test Condition					
			Shear		Tension		Flexure	
			RT	HW	RTD	HW	RTD	HW
	Adhesive	Bond Line	Prep 1	Prep 1	Prep 1	Prep 1	Prep 1	Prep 1
Scarf	A	T1	3		3		3	
	A	T2	3	3	3	3	3	3
	A	T3	3		3		3	
Lap	A	T2		3		3		3

			Test Condition		
			Shear	Tension	Flexure
			RTD	RTD	RTD
	Adhesive	Bond Line	Prep 1	Prep 1	Prep 1
Notch	A	T1	3	3	3
	A	T2	3	3	3
	A	T3	3	3	3

HW = Hot Wet
RTD = Room Temperature Dry

T1 = .1" , T2 = .25" , T3 = .35"

2.3 Structural Response of Connections

Planning has commenced for evaluation of the structural response of connections using a series of strength tests. The initial phase of this effort will study three connection types: 1) bolted only connection; 2) metallic close-out and 3) embedded metallic connection. Details of the test setup and comprehensive test plan will be developed during the next quarter.

2.4 Composite Panel Fabrication

Composite fabrication of test article is ongoing. Test articles for the initial stress relaxation study and adhesive testing are completed. Methods for fabrication of connections with metal close-outs and embedded metal are being investigated.

2.4.1 Materials

Resin used for relaxation study was changed to the Dow 8084 as per Team decision. A BTI +/- 45 weave was procured so that both this weave and the 0/90 weave are from the same manufacturer. Both are 24 oz. cloth. The Dow Derekane 411 use for the adhesive study is still continuing. This is to be compatible with the materials used in the AHFID program.

3. Structural Monitoring

3.1 Embedded fiber optic sensors

NUWC has conducted limited experimental testing using surface mounted fiber optic (F/O) strain gages on cantilevered bending and tensile metallic specimens. Test results indicated that a 4-8% deviation existed when compared to conventional foil strain gage results obtained from the same specimens. This discrepancy is consistent with those identified by others. Researching the source(s) of this discrepancy with the F/O manufacturers, identified that:

(1) The process for establishing the F/O gage factor may be inaccurate.
(2) The F/O strain gages may be limited by temperature compensation issues.

NUWC has developed an experimental test plan that considers generically simple bolted

joint concepts using thick MACH GRP laminates instrumented with embedded fiber optic, conventional foil and PZT strain sensors.

- More confidence in strain measurement validations are required to assess complex internal stress states in MACH joints.
- This test plan will serve to identify performance, reliability and any limitations of each strain sensor type.

The process of embedding sensors will be developed for exploratory use to support MACH and MONET (Miniature Optical Nodes for Environmental Testing), an OSD Test Technology Development Demonstration (TTDD) Program.

A measuring scheme has also been developed for monitoring of creep in composite material due to bolt stresses. Recommendations from NUWC are as follows:

- To benchmark candidate strain sensor types for use in creep evaluation of MACH laminates.
- Consider foil, fiber optic and PZT strain gages.
- Evaluate sensor performance and reliability under:
  Static loading conditions.
  Cyclic fatigue loading conditions at specific frequencies.
- Design test articles using generically simple joint concepts whereby analytical or numerical solutions may be readily applied for results correlation.

3.2 Intra Panel Processing

Several milestones have been achieved with the IPP system as follows:

- Single board with ADC and temperature sensor developed and operational. Monitors temperature continuously.
- Serves web page that displays the current temperature.
- Can also send e-mail.

Futuer work includes: 1) Establishing a network of processors with a variety of sensors and actuators; 2) Communicate using a variety of TCP/IP protocols; 3) Reduce network wiring; 4) Create reusable software routines; 5) Development of signal conditioning techniques.

4. Cavitation Erosion Protection

4.1 Task Description

The work summarized in this section was performed by Light and Shorey summarized in an ATS report [Thompson, Light and Shorey, 2002]. In this task, ATS shall conduct an engineering study that focuses on methods of erosion control and impact resistance of composite panel structures.

Based on the results of this survey, the constituents for the composite shell, erosion protection overlay and any intermediate interface layer shall be evaluated and one or more candidate material systems will be designed. As part of the evaluation process, attention will be given to the full scale manufacturing process of any potential design.

4.1.1 Previous Work

This work is a follow on to the work published in a Progress Update dated December 14, 2001, and a presentation given at the program quarterly review on February 12, 2002. The reader is encouraged to refer to these documents for information regarding the background and scope of the project.

4.2 Material System Design and Testing

4.2.1 Summary of Cavitation Erosion Testing Standard

The testing of the material system specimens will be done in accordance with a modified ASTM G32-98 standard. The modification provides for a stationary sample below the oscillating horn. This modification has been used in many previous studies and provides for easier mounting of composite material specimens. Although the cavitation erosion mechanism present in this method is not the same as that on an immersed moving body, this method has been shown to be useful in ranking various materials with respect to their erosion resistance.

This test method utilizes a commercially available ultrasonic transducer which is attached to a tuned "horn" oscillating at 20 kHz. The particular ultrasonic equipment used is a Branson Ultrasonic Digital Sonifier model S450D. The horn is constructed of Ti-6Al-4V and has a replaceable button tip. The tip of the horn oscillates above the test sample and produces cavitation bubbles which impinge on the surface. The peak to peak tip displacement is OEM calibrated and adjustable on the amplifier. It is set at 0.050 mm for these tests. The test sample is mounted 0.50 mm away from the oscillating tip. Bulk fluid temperature in the container is maintained at 23-27° C by the use of a cooled water

recirculation system. The temperature is monitored by a thermocouple in the tank. The erosion rate of the material will be determined by periodically stopping the test and drying and weighing the sample. Maximum predicted test duration for each material system is 24 hours. The testing method will be calibrated periodically using standard 6061-T6 Aluminum or Ni 200 as a reference material.

4.2.2 Test Apparatus

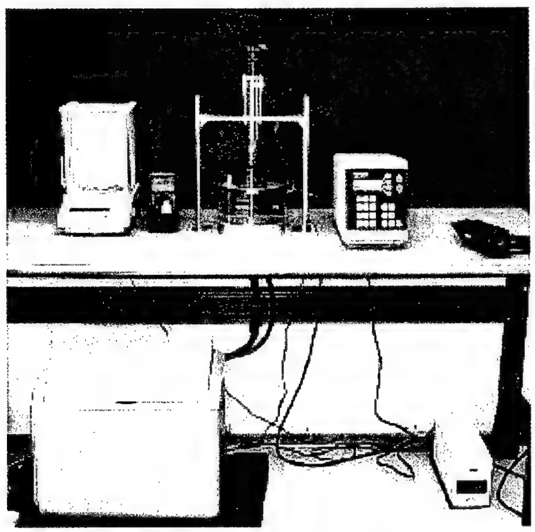


Figure 1 – Experimental Test Apparatus

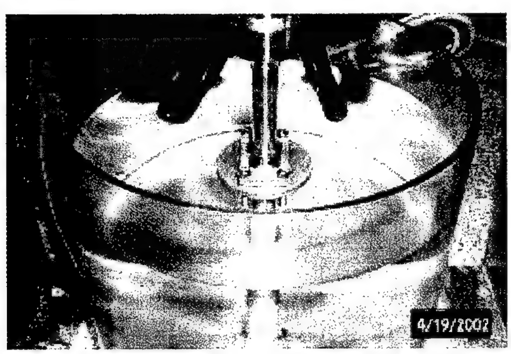


Figure 2 – Close up of specimen holder

4.2.3 Test Method

The following procedure has been adapted from ASTM standard G32-98. This represents the current test procedure in use for each specimen:

1. Clean test vessel, specimen stand, and cooling pump. Rubbing alcohol and cold water rinsing should be sufficient.
2. Assemble converter and horn as specified by the product manual.
3. Prepare test specimen cleaning solution. Cleaning solution is denture cleaner tablets dissolved in warm tap water (recommended by ASTM standard). The cleaning procedure is a three-part procedure. First, gently "swish" the specimen in the cleaning solution for approximately 20 seconds. Next, repeat the first step with cold tap water to rinse. The cleaning solution and rinse water are discarded after each test. Last, dry the specimen. Avoid paper or cotton products as they may leave lint of the specimen. A heat gun or hair dryer should be sufficient.
4. Clean, dry, and weigh the horn tip. The weighing device should be accurate to at least 0.1mg. Weigh horn tip or specimen until consecutive readings yield identical results within repeatability and accuracy of the device. The horn tip mass is used to qualitatively determine the point at which the performance of the horn tip has degraded enough to significantly effect test results. Visual inspection of the horn tip is also used, focusing on horn tip darkening, erosion rings, and pitting.
5. Attach horn tip as specified by the product manual.
6. Fill test vessel and pump with fresh liquid. The pump is a filtered salt-water fish tank pump. This is part of the closed loop cooling system that controls the temperature of the liquid at 25°C ± 2°C. The pump is placed in a thermoelectric cooler to cool the liquid in the loop. The thermoelectric cooler is filled with tap water below the level of the exhaust fan for higher cooling capacity and quicker response. The cooler operates continuously with the pump being operated as needed. The liquid in the vessel is discarded after each test due to the sentiments from the eroded specimen. The liquid in the pump is not discarded after every test because it is filtered. However, check the filter and inspect the condition of the liquid during the 10 minutes of gas stabilization. If the water has particles in it, discard and replace with fresh liquid, and clean or replace the filter. A fish tank heater may be used to heat the liquid if needed. This cooling system is one of many available options, but this one is found reliable, simple, and relatively inexpensive.
7. Attach hoses from the pump. Operate the pump (outside the cooler) for about 10 minutes to help stabilize the gas content of the liquid.
8. Obtain a 1"x1"x1\4" thick (approximate) specimen. Machine and polish a 1"x1" surface so that neither pitting nor scratches are visible.
9. Clean, dry, and weigh the specimen.
10. Record the mass, test material (first time), and elapsed time.
11. Secure the specimen to the test stand, polished side up.

12. Place pump in cooler and turn off, if the liquid temperature is in the correct range.
13. Locate the horn tip 0.5mm above the specimen and secure in place.
14. Measure the liquid height in the vessel. The liquid height should be at least 100mm and the immersion depth of the specimen should be 12mm ± 4mm. Adjust the liquid level as needed.
15. Power up the Digital Sonifier. Set the interval time and horn amplitude. Refer to the ASTM standard for approximate interval times. Refer to the product manual for amplitude settings. For this test the tip-to-tip displacement is 50 microns.
16. Start the test.
17. Monitor the liquid temperature and use cooling as needed.
18. At the end of the interval, clean, dry, and weigh the specimen.
19. Record mass and elapsed time. Repeat steps 11 through 19, omitting 12, 13, and 14, until two successive weighings yield identical (or acceptably similar) readings.

4.3 Description of Test Results

The discussion in this section has been adapted from the ASTM G32-98 standard.

Interpretation and reporting of cavitation erosion test data is made difficult by two factors. The first is that the rate of erosion (material loss) is not constant with time, but goes through several stages. This makes it impossible to represent the test result fully by a single number, or to predict long-term behavior from a short-term test. The second is that there is no independent or absolute definition of "erosion resistance", nor can units of measurement be ascribed to it. The following paragraphs describe the required data interpretation steps.

The primary result of an erosion test is the cumulative erosion-time curve. Although the raw data will be in terms of the mass loss versus time, for analysis and reporting purposes this should be converted to a "mean depth of erosion" (MDE) versus time curve, since a volumetric loss is more significant than a mass loss when materials of different densities are compared. Calculate the mean depth of erosion, for the purpose of this test method, on the basis of the full area of the test surface of the specimen, even though generally a narrow annular region at the periphery of the test surface remains virtually undamaged. For the horn tip used in this test the area is $0.866cm^2$ ($0.1342in^2$).

Because of the shape of the cumulative erosion-time curve, it is not meaningful to compare the mass loss or MDE for different materials after the same cumulative exposure time. (The reason is that a selected time may still be within the incubation or acceleration stage for a very resistant material, whereas for a weak material the same time may be within the maximum rate or deceleration stage.) However, for a crude single-number comparison one may compare the cumulative exposure time to reach the same MDE; in order to standardize this approach a value of 100μm is chosen, which should be within the maximum erosion rate stage. For very resistant materials, for which the testing time would be excessive, 50μm may be substituted.

For a more complete description of the test result use the following parameters:

- The "maximum rate of erosion", that is, the slope of the straight line that best approximates the linear (or nearly linear) steepest portion of the cumulative erosion-time curve, expressed in micrometers per hour. This is the most commonly use single-number result found in the literature, and its use is required in this test method.
- The "nominal incubation time", that is, intercept of the maximum erosion rate line on the time axis. This is also required.
- The "terminal erosion rate" if exhibited in a test that is continued for a sufficiently long time. This is optional.

If the terminal erosion rate is reported, then the MDE corresponding to the intersection of the terminal-rate line with the maximum-rate line, or alternatively its intercept on the MDE axis, must also be reported.

The use of other carefully defined test results representations, in addition to those required above, is optional. Some that have been used include the "tangent erosion rate" (the slope of the straight line drawn through the origin and tangent to the knee of the cumulative erosion-time curve), the MDE of that tangency point, and the curves of the "instantaneous erosion rate" versus time or of "average erosion rate" versus time.

This test method is sufficiently tightly specified that direct comparisons between results obtained in different laboratories are meaningful, provided that the standard test configuration, conditions, and procedures are rigorously adhered to. However, to facilitate comparisons between results from different types of cavitation erosion tests, it is also necessary to present results in normalized form, relative to one or more standard reference materials included in the test program. Specific parameters used include normalized erosion resistance and normalized incubation resistance.

4.4 Summary of Tests to Date

4.4.1 Calibration Tests

The ASTM G32 standard recommends calibrating the test apparatus with Nickel 200 material and comparing the results with those provided in the standard. The standard lists results from five independent labs and these are shown in Figure 3. The error bars on the curves represent a single standard deviation.

Because we are using a modified test method, a direct comparison of the calibration results is difficult. The area of the cavitation tip in the standard is larger than that tested by a factor of 2.3. This tip area will affect the overall mass loss area and thus the reported quantity of MDE. In an effort to account for this difference in cavitation

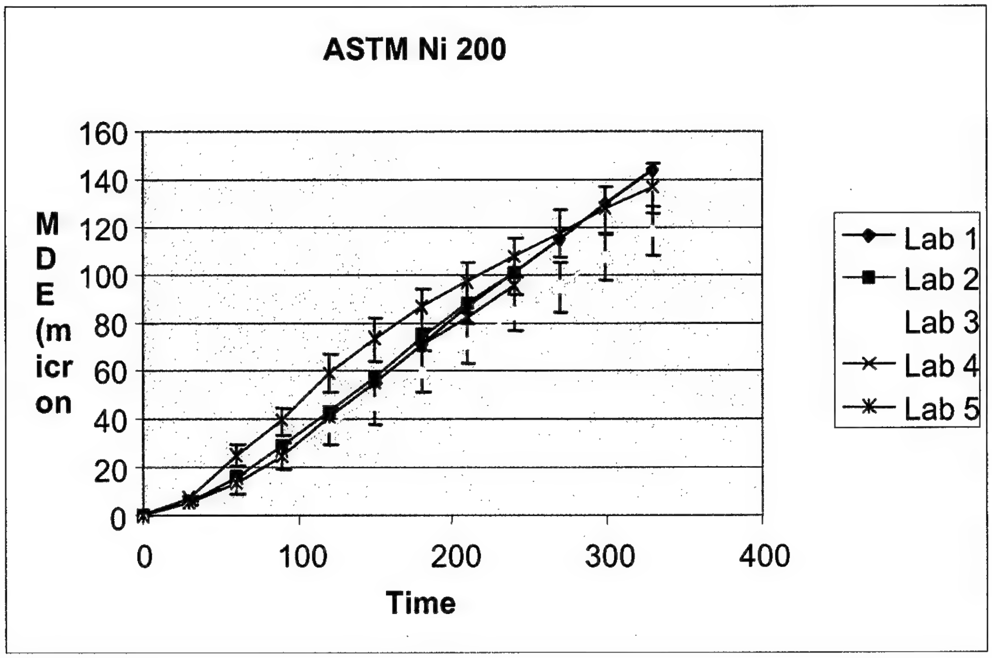


Figure 3 – MDE for Ni 200 from independent lab tests

affected area, the results for the calibration tests have been normalized with respect to tip area and are compared in Table 1. The results show that the normalization process provided starting values of MDE that are comparable; however, the results from intermediate times vary significantly. Part of this trend can be attributed to the drop in

Table 1 – Comparison of normalized MDE for Ni 200

Time (min)	ASTM Independent Test Labs Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	ATS Test
	MDE / inch^2					
0	0	0	0	0	0	0
30	17.52692503	17.52693	17.52693	23.34743	17.52693	15.51805
60	43.78461308	52.54808	43.78461	81.74872	43.78461	23.27707
90	81.74871748	93.42243	81.74872	128.4763	81.74872	29.09633
120	134.2967931	143.0603	122.6231	192.6654	134.2968	46.55414
150	181.02436	186.8449	151.8237	239.3929	181.0244	76.62035
180	230.6621812	242.3359	195.6083	280.2673	230.6622	111.536
210	280.267303	286.1205	233.5724	315.3212	268.5936	167.7889
240	329.9051243	329.9051	274.4468	350.3423	309.4679	229.861
270	373.6897374	NA	309.4679	382.4532	NA	294.8429
300	423.3275586	NA	350.3423	414.5641	NA	360.7946

erosion rate of our test samples shown in Figure 4. This trend has been consistent for every Ni 200 sample that has been run; however, other materials do not show this behavior. Samples of aluminum and stainless steel do not exhibit this drop in erosion rate at the early stages of testing. Possible explanations for this behavior include material

discrepancies and a nonlinear difference in cavitation intensity with tip area. More work is planned in this area.

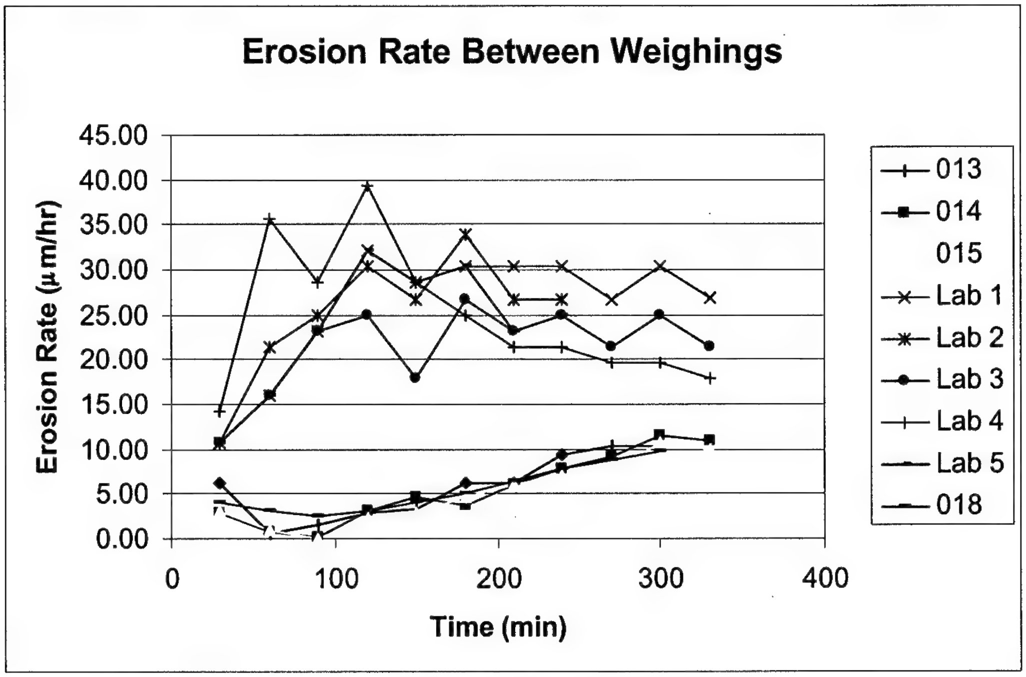


Figure 4 – Erosion rate of Ni 200 samples

Tests were also conducted to quantify the repeatability of the test apparatus and method. Aluminum 6061-T6 samples were used for this study because of their availability and short test times. Figure 5 shows the results from this repeatability test. The error bars on the test represent a single standard deviation.

At this time, the test apparatus appears to be repeatable although some questions still remain as to the correlation of the Ni 200 data with that of the ASTM standard results. More work is planned in this area.

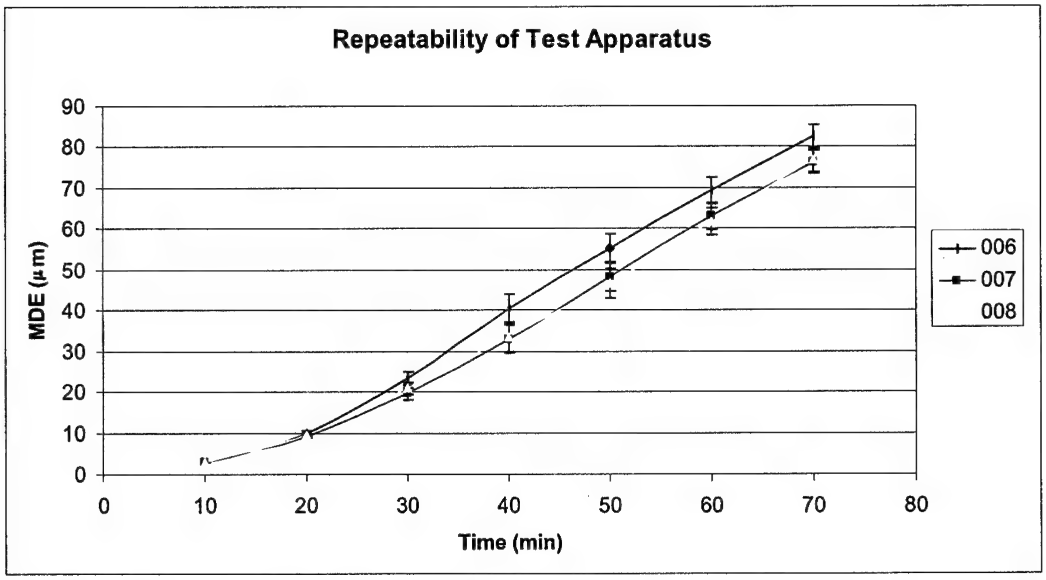


Figure 5 – Repeatability of test apparatus using aluminum samples

4.4.2 Pilot Tests

In addition to the calibration test efforts, other materials have been experimented with. Figure 6 shows a brief history of different materials that have undergone preliminary evaluation. Each of these materials will be more thoroughly studied in the coming weeks.

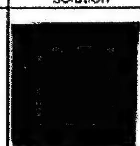
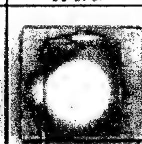
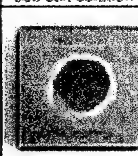
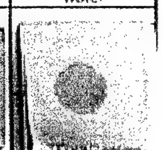
Material and Liquid	EDPM rubber in 3.6% sea salt solution	6061-T6 Al. in 3.6% sea salt solution	316 SS in 3.6% sea salt solution	Ni 200 in distilled water
				
elapsed time	11 hours	70 minutes	16 hours	5.5 hours
maximum rate of erosion (µm/hr)	not available	112.64	1.3	9.89
time to 50µm MDE (hr)		0.4	38.5	5.1

Figure 6 – Photo of various pilot tests of different materials.

4.5 Preliminary Test Matrix

The following is a list of initial material systems which will be evaluated for their cavitation erosion resistance using the method mentioned previously. Based on background research, these represent some of the most promising composite layups.

- Glass/Vinyl Ester laminate
- Carbon Fiber/Vinyl Ester laminate
- Glass, Carbon Fiber weave/Vinyl Ester
- Glass/Vinyl Ester/PVC core sandwich
- Carbon Fiber/Vinyl Ester/PVC core sandwich
- Glass, Carbon Fiber weave/Vinyl Ester/PVC core sandwich

Materials that are being evaluated for the metal skin include NiAl Bronze (Propeller bronze), 316 Stainless Steel and two high strength stainless steel alloys, Ferralium and Zeron 100. The cavitation erosion performances of the first two are well documented in the literature; however, both Ferralium and Zeron 100 will have to be tested for their cavitation erosion resistance.

The construction of the surface treatment samples will occur after the composite laminates are fabricated. Initial tests will involve sputter coating the composite material with NiAl bronze and/or stainless steel. Specific coating thicknesses have not been defined at this point and will be driven by process variables in this situation.

5. HYSWAC H-body Design

5.1 Single H-body

Construction and installation of the single H-body on the experimental vessel Waverider has been completed and testing will begin shortly. This H-body was constructed of composites using primarily hand-layup techniques.

5.2 Construction of the single H-body for WAVERIDER

Pacific Marine's work for this period consisted primarily of construction and installation of the single H-body for the WAVERIDER. This was completed this quarter by PACMAR. This process was discussed in a series of reports submitted by Eric Schiff of PACMAR. Figures 5.1 through 5.9 are figures selected from this document to give a pictorial display of the construction and installation.

Figure 5.1 – Laying of foam strips onto exterior frames

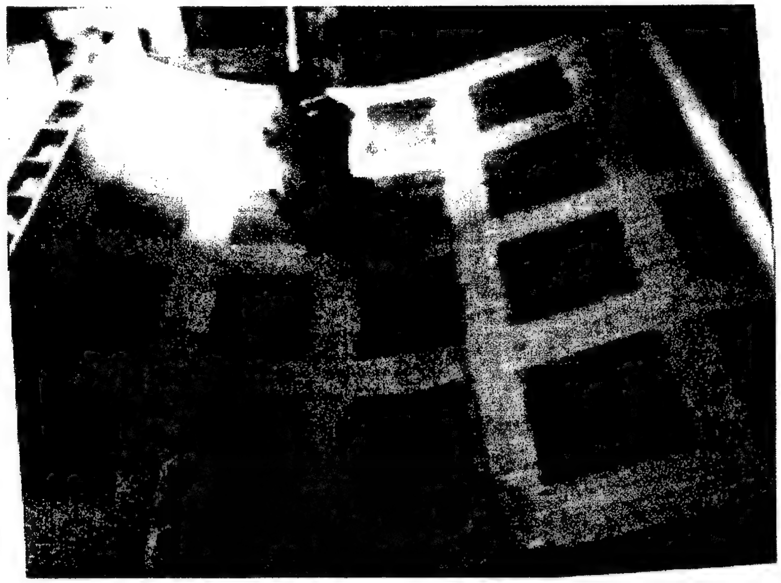


Figure 5.2 – Preparing for installation of interior frames

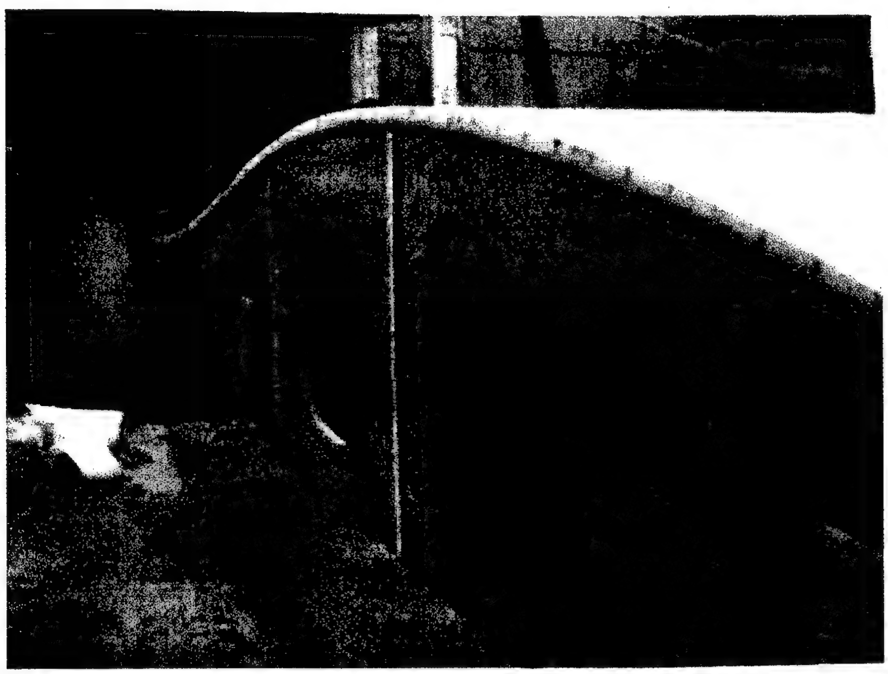


Figure 5.3 – End view of body.

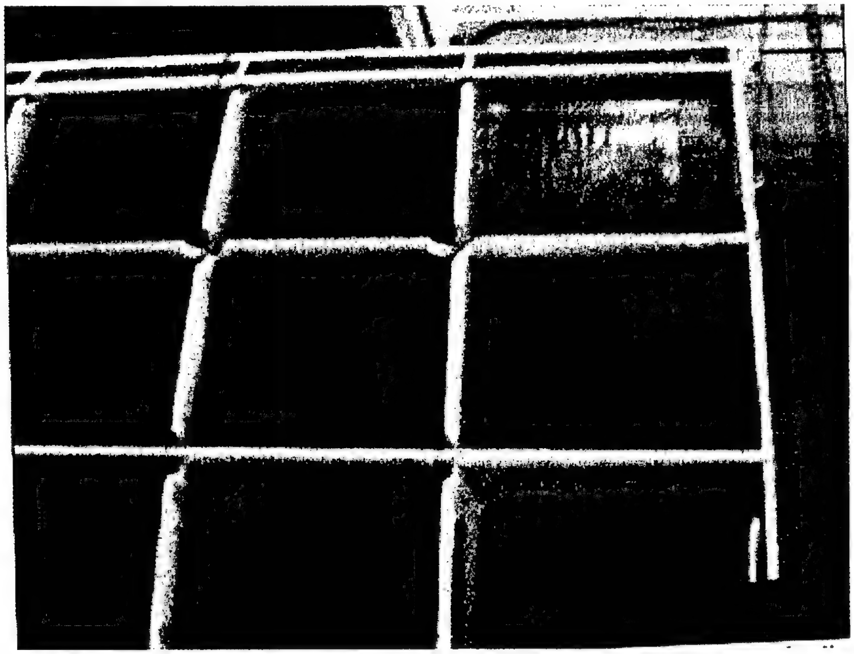


Figure 5.4 – H-body being turned over for attachment of lower shell.

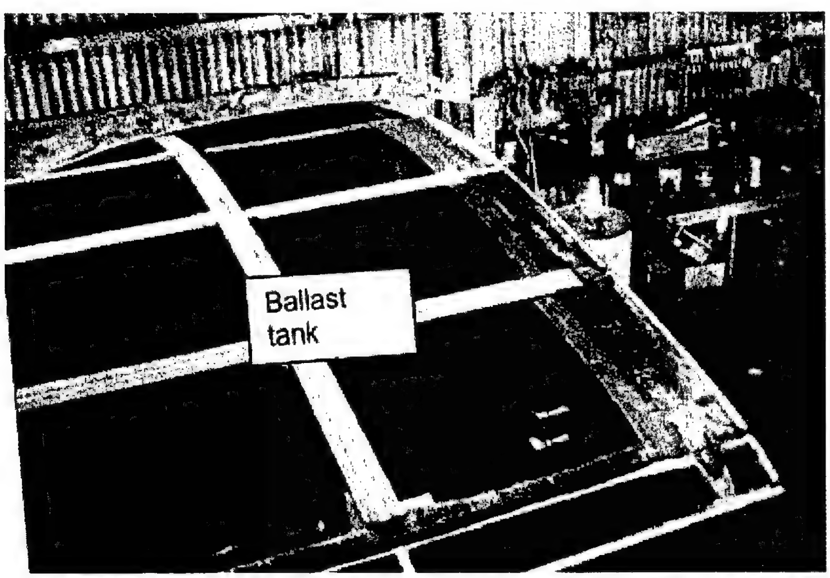


Figure 5.5 – H-body inverted and ready for lower shell attachment.

Figure 5.6 – Completion of H-body construction

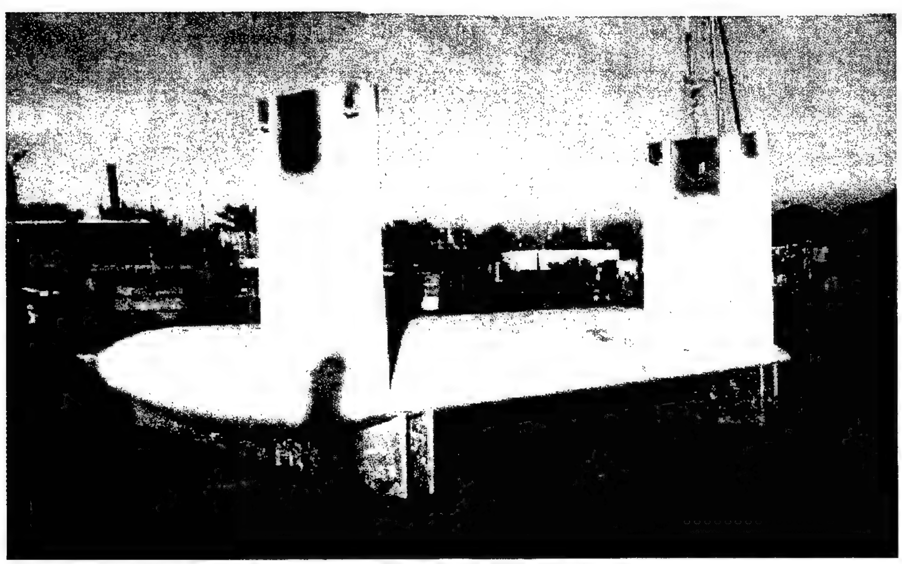


Figure 5.7 – H-body ready for installation.

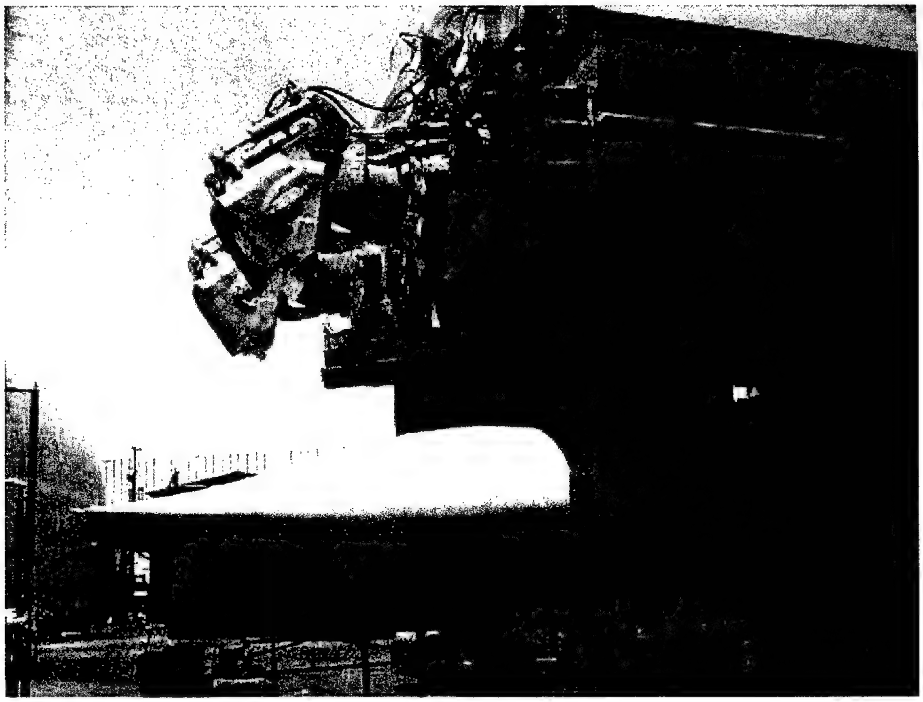


Figure 5.8 – H-body positioned for installation.

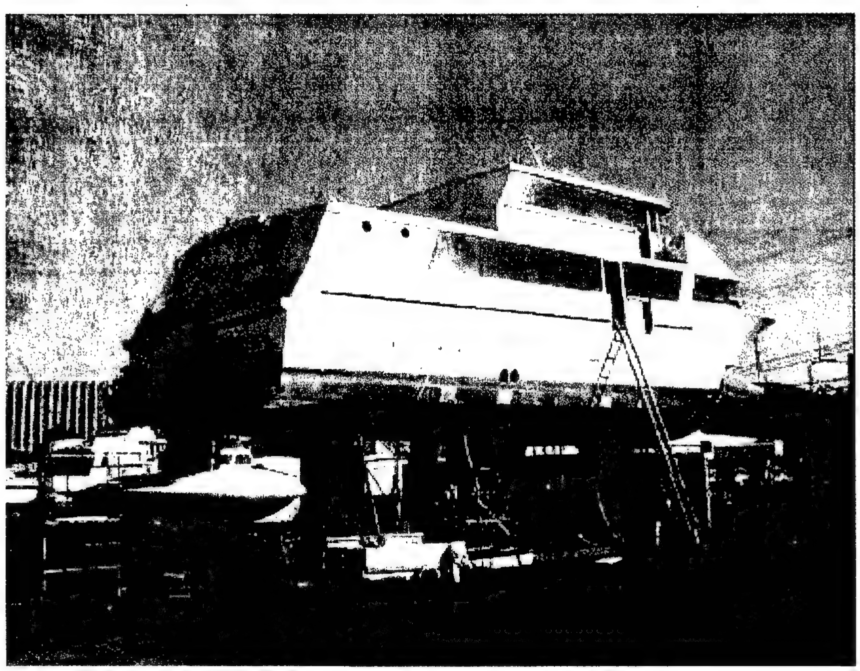


Figure 5.9 – Rear view of vessel with H-body.

6. Hybrid Structural Design – Preliminary Studies

This work presented in this section is the preliminary investigation into a hybrid structure design. The intention of this initial work is to develop analytical tools and techniques while waiting for final selection of sizing and geometric constraints of the underwater body design.

As a starting point, the MACH team has decided to investigate the design of a hybrid lifting body the target geometry is Pacific Marines' H-body design. By designing a hybrid structure the design details and manufacturing issues that need further research will be exposed. Other benefits expected from task will be a quantitative assessment of the safety factors for the panel and connection design concepts and the model will have the fidelity to conduct high rate dynamic analyses.

6.1 Description of the FE Modeling Techniques

Figure 6.1 show the current Pacific Marine H-body finite element model developed using ABAQUS CAE. The model is a shell model using 7968 S4R shell elements with a total of 45384 degrees of freedom. There are three elements sets the first is the skin which simulates a one inch thick quasi-isotropic E-glass/vinylester composite material system. The second element set is the primary structure this element set simulates a three-quarter

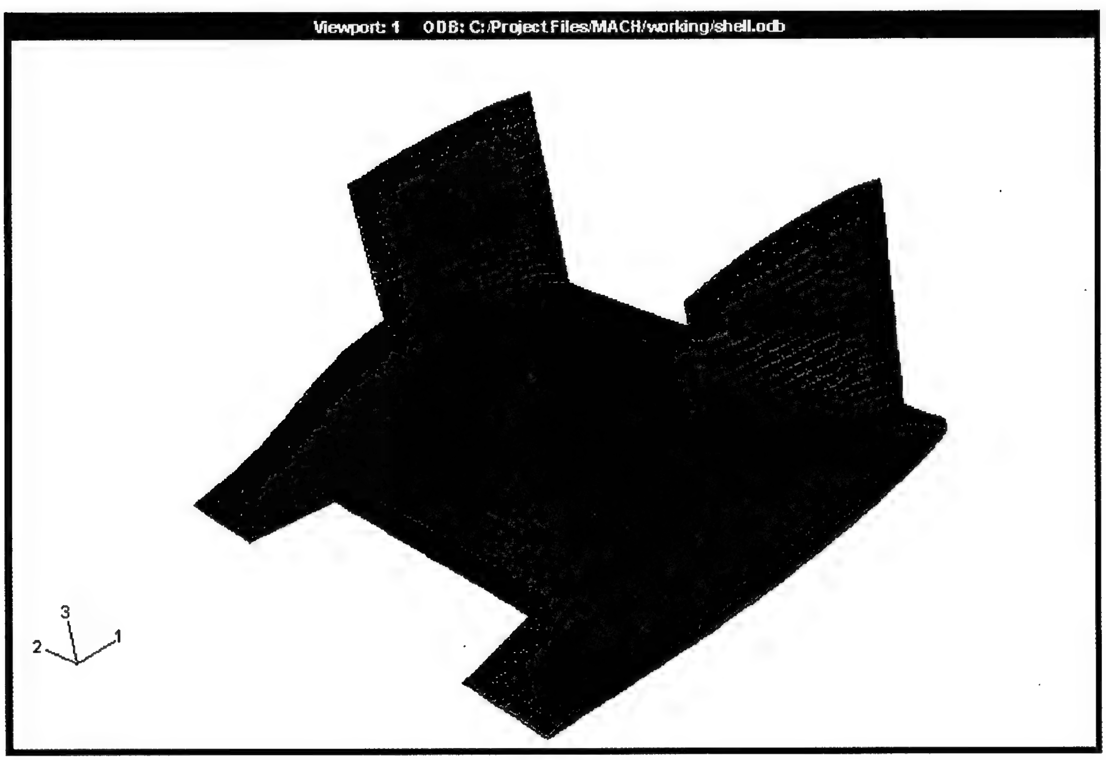


Figure 6.1 - Hbody Finite Element Model

inch thick steel plate. The third element set is the secondary structure this element set simulates a one-half inch thick steel plate. Figures 6.2 and 6.3 show the primary and secondary structure respectively.

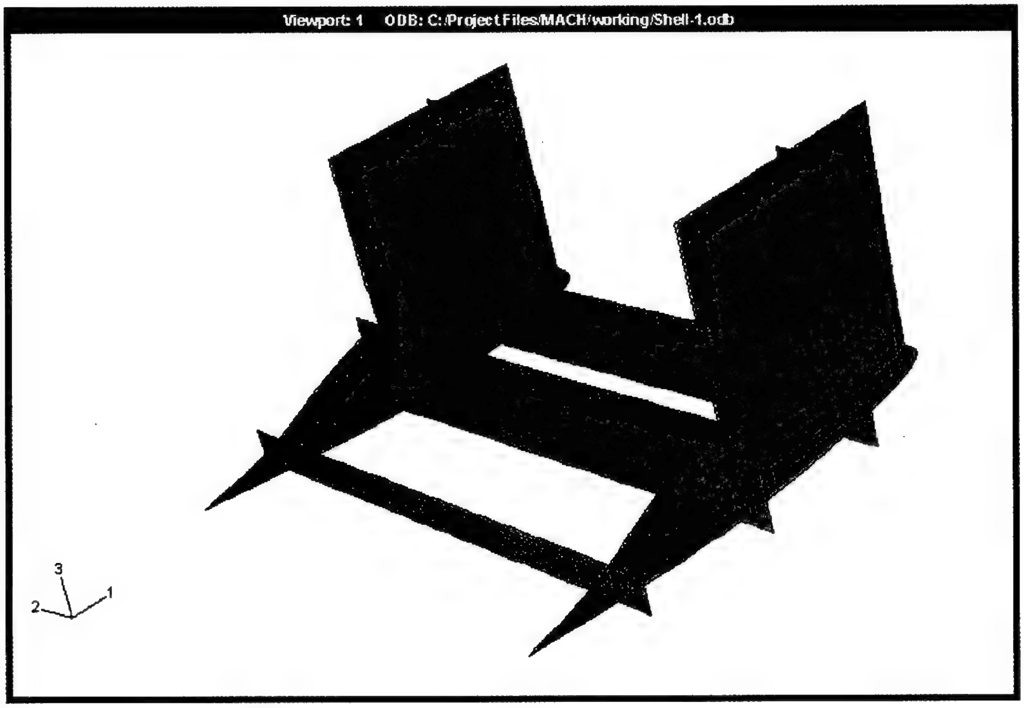


Figure 6.2 - Primary structure element set

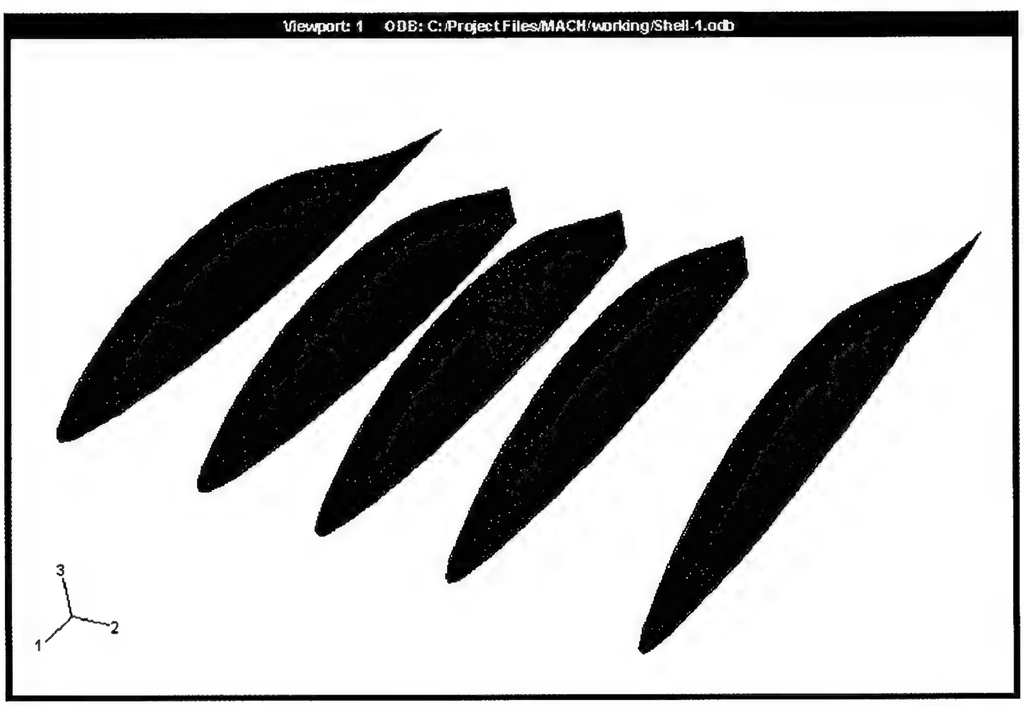


Figure 6.3 - Secondary structure element set

As can be seen from Figures 6.2 and 6.3 there has been no attempt to lighten or optimize the structure.

6.2 Loading Used in Preliminary Analysis

A simplified loading scheme was developed for this first-cut analysis. The total load is based upon values found in the CETEC Report titled *SES200- Global Finite Element Analysis Report*, report # CET/0617/R/01. The load was simplified and Figure 6.4 shows the current loading scenario where the lift is modelled by a low pressure region at the top of the lifting body.

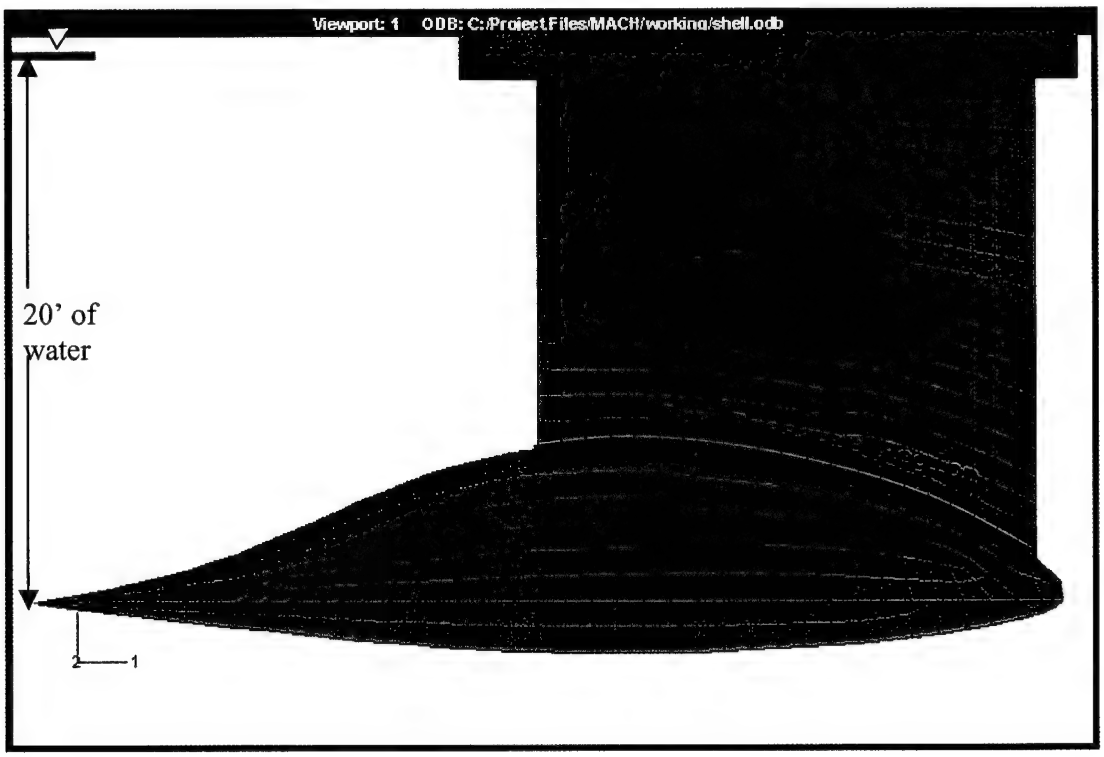


Figure 6.3 - Loading schematic

The displacements on the nodes are at the top of the struts are fixed to simulate a built-in boundary condition. Hydrostatic pressure is applied to the model as if the tip of the tail section were in 20 feet of water. The hydrostatic pressure has been reduced in the low-pressure region to simulate 350 ltons of lift. Inertial loads have been applied to the model assuming 1.5g's in the 3 direction (vertical) and 0.5 g's in the 1 (fore/aft) and 2 (transverse) directions.

A thorough assessment of the loads is recommended for future work.

6.3 Preliminary Results

A linear static analysis was conducted with a loading scenario that combined all of the loads previously discussed. Figure 6.5 shows the underside of the lifting body the color contours are the Von Mises stress on a deformed shape. The peak stress is 27 Ksi and the peak deflection is 2.5 inches. It is worth noting that there are no stiffeners currently in this model. Stiffeners need to be added to maintain the optimal hydrodynamic shape.

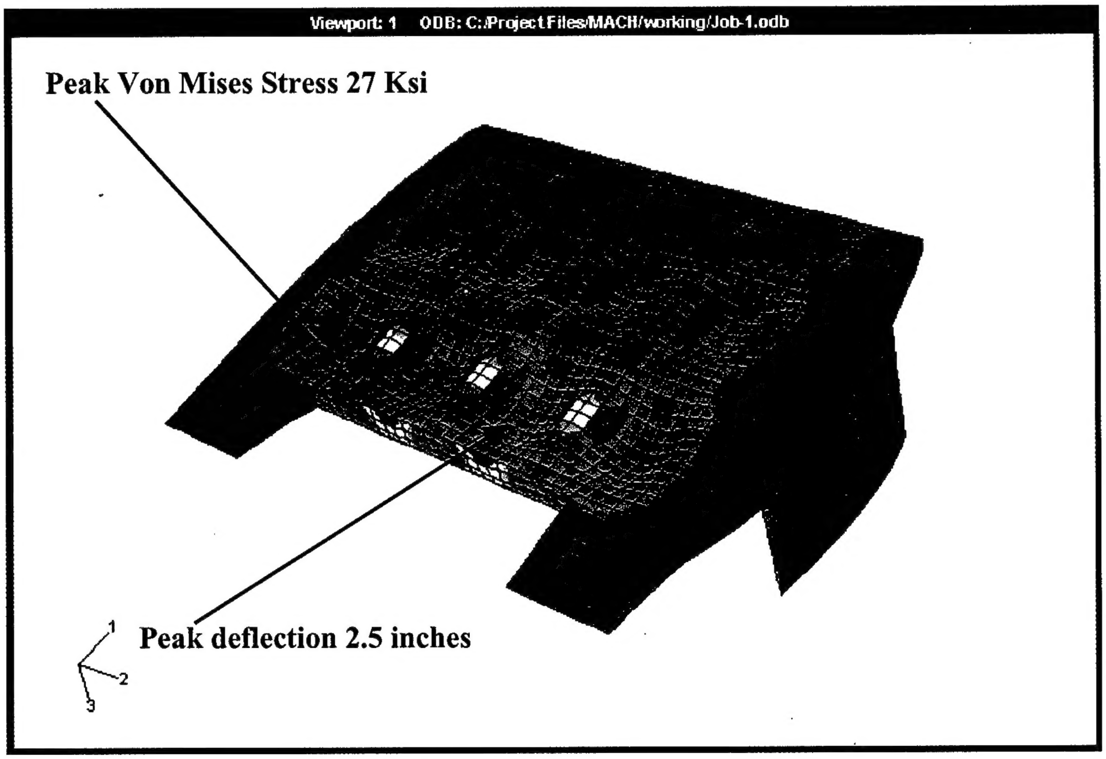


Figure 6.3 - Von Mises stress contour

7. Summary and Conclusions

Connection studies appropriate to the MACH effort are progressing. New test articles are being prepared for the bolt relaxation study using the 8084 resin. Testing is due to resume the first part of the next reporting period. Adhesive test articles for the lap-shear tests are in preparation. The initial down-select testing is due to commence shortly. Planning for the structural testing of connections has commenced. Testing of bolted joints, close-out connections and connections with embedded metal are scheduled. Analysis of connections, including viscoelastic effects and contact is ongoing.

Structural monitoring has focused primarily on evaluation of the accuracy of embedded sensors. Techniques for evaluating connection response have been proposed along with proof-of-concept testing. Work on the integrated parallel processing system is ongoing. This effort will begin to look at signal conditioning techniques in the next period.

The cavitation erosion protection screening test system is operational. Pilot testing of Ni 200 and 6061-T6 aluminum is used to verify the functioning of the system. Testing of the erosion resistance of other materials and coatings will occur during the next period.

The construction and installation of the single H-body on the WAVERIDER was successful. At sea testing of this vessel will occur during the next reporting period.

Investigation into the hybrid structural design of the H-body for the HYSWAC was initiated. This design is meant as a precursor while awaiting for further details of the underwater body design of the LSC(X). Techniques for load case determination and finite element modeling will be established.

A bi-annual meeting was conducted in Honolulu Hi. Several issues were discussed. PACMAR noted that there is a need for a lifting body at 2-4x scale of the Midfoil. The Midfoil lifting body is a "G" Body, however the most appropriate body shape may be a blending of an H-body and G-body. Current underwater bodies are constructed using GRP over plywood framing which will not scale to 4x and is doubtful at 2x. There is a possibility that connections designed for HYSWAC panel may not be the one used for a 2-4x lifting body.

At 50 knots there is a high probability of cavitation erosion (and always will be an issue as ships go faster). This may be solved using some sort of outer protection panels for cavitation resistance purposes. Also, there is a future need to have shock resistant panels (connections) for Navy ships. Some dynamic shock analyses and experiments should be explored/planned/conducted.

The definition of removable was discussed and it is concluded that there is not a need to have all panels removable. Most panels can be replaceable, as panel size can becomes large and adhesively bonded to hybrid structures. This will effect the design parameters

of the hybrid structure. There is and always will be a weight reduction goal. Which can be translated into vessel improved performances such as higher speed and/or longer range.

A path was proposed and discussed to maximize the benefit of the MACH Demonstrator. A case study around a scaled up lifting body, perhaps a 3x is recommended. PACMAR recommended an H-body shape as a beginning point for the study. Go through a preliminary design / extensive feasibility design and cost & benefit study of the lifting body using steel, aluminum, and hybrid structures, and quantify the cost benefits of each. This is going to be a "total re-engineering" not just a materials replacement comparisons. There is a possibility of using California State University Long Beach's expertise in optimization. Connection concepts can still initially be proceeded (as currently planned) to be general and generic with the goal to transform/mature them to the current candidate of 3X lifting body and connection concepts specific to this 3x lifting body should be forthcoming. While work on developing the hybrid design techniques is ongoing, fabrication and testing of connection subassemblies of candidate joints should be done in parallel. The generic connection and fabrication research and testing and the stress relaxation research in bolted connections should continue.

8. References

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*: 05-01-2002

2. REPORT TYPE: Progress Report

3. DATES COVERED *(From - To)*: 1-January-2001 to 31-March-2001

4. TITLE AND SUBTITLE

Modular Advanced Composite Hullform Technology (MACH) - Progress Report for Quarter 3

5a. CONTRACT NUMBER

5b. GRANT NUMBER: N00014-01-1-0916

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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5717 Corbett Hall
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8. PERFORMING ORGANIZATION REPORT NUMBER

UM-MACH-PR-01-3

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
Ballston Center Tower One
800 North Quincy St.
Arlington, VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)

ONR

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT

Approved for Public Release, Distribution is Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This progress report summarizes the third quarter of work on the Modular Advanced Composite Hullform (MACH) project.

15. SUBJECT TERMS

Composites; Hybrid Structures; Connections; Structural Monitoring

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	35	Vincent Caccese
					19b. TELEPONE NUMBER *(Include area code)* (207) 581-2131